كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
PRINT ISSN 3009-6049
ONLINE ISSN 3009-6022

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (53),Issue (3)
July 2024, pp:129-136
https://erjsh.journals.ekb.eg

Pushover Analysis of Masonry Structures: Case Study, Trani's Cathedral Bell Tower

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Abstract: Masonry construction has been the most popular form of building. Protection of masonry heritage structures against earthquakes is a strategic research topic. Architectural history includes many old masonry structures, so keeping them safe from collapse is essential. Researches about the assessment of masonry structures have become more frequent in the last few decades. However, the results about the seismic behaviour of masonry structures are still limited, and further research is needed. Pushover analysis is a very common approach to assess the seismic performance of structures subjected to seismic loads. The main objectives of this research are to evaluate the seismic performance of Trani's Cathedral Bell Tower in accordance with the Applied Technology Council (ATC-40) and determine the target displacement of the tower using the pushover analysis method. The finite element software ABAQUS was used to perform a numerical analysis under the expected loads. The numerical results, such as stresses, deformations, cracks, and pushover curve indicate the overall stability and safety of the structure in its current state. Finally, the developed model can predict the locations of cracks and provide an efficient tool for the assessment of existing masonry structures. The results showed that the investigated tower satisfied the seismic loads.

Keywords: Pushover analysis; Seismic assessment; Performance levels; masonry structures.

1. Introduction

Masonry construction has been the most popular form of buildings. Protection of the historic masonry structure against earthquakes has become a strategic research topic. Researches about the assessment of masonry structures have become more frequent in the last few decades. Efficient numerical tools and procedures are needed to evaluate the stability and safety of these structures. The main objectives of this research are to evaluate the seismic performance of Trani's Cathedral Bell Tower [1] and determine the target displacement using pushover analysis method.

The numerical analysis is a practical method for evaluating the seismic behavior of masonry structures [2-7]. Many researchers studied the historical masonry towers and the effects of earthquakes [8-12]. The seismic performance of masonry structures has been assessed in several studies using the pushover analysis method, as follows: G. Milani et al. [13] performed pushover analysis and finite element investigations to assess the seismic performance of a Masonry Tower located in the Emilia region of Italy. Yohei Endo et al. [14] used pushover analyses and nonlinear dynamic analyses to investigate the seismic performance of masonry structures using different nonlinear seismic techniques. P. B. Lourenco et al. [15] investigated the seismic performance of a two-story unreinforced masonry building using simplified approaches. For this purpose, pushover analyses were carried out using different modeling techniques. Degli et al. [16] performed a numerical analysis based on the use of the pushover analysis method. The efficiency of the proposed technique was presented through an application to a medieval fortress that had been struck by the 2012 Emilia earthquake in Italy.

2. RESEARCH SIGNIFICANCE

The research aims to assess the seismic performance of Trani's Cathedral Bell Tower and determine the target displacement of the tower using pushover analysis method. The analysis is performed through three stages: At first, develop and create a numerical model of an existing masonry structure that takes into account the nonlinear behaviour and complex geometry. Second, determine the target displacement of the proposed masonry structure "Trani's Cathedral Bell Tower" by applying pushover analysis and plotting the pushover curve that describes how the structure behaves. At last, assess the seismic performance level of the proposed structure.

3. PUSHOVER ANALYSIS

Pushover analysis is one of the most commonly used techniques for evaluating a structure's seismic performance during an earthquake. This method subjects the structure to gravity loads and applies a lateral monotonic displacement that is increased gradually until the ultimate condition of elastic and inelastic behavior is reached (FEMA 440) [17].

At every step, some elements could yield successively, changing the stiffness of the structures. Fig. 1 shows the pushover curve, which represents the relationship between base shear and top displacement. It is possible to create it by plotting the base shear and the top displacement at every step. Pushover analysis is used to express the structure's global response to lateral loads.

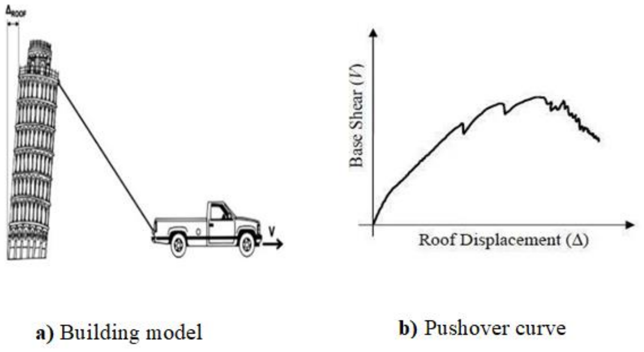

Fig.1 Representation of pushover analysis in ATC 40 [19]

3.1 STEPS OF PUSHOVER ANALYSIS

In 1978, Freeman presented the capacity spectrum method. Material nonlinearity is introduced into the analysis through the nonlinear static procedure called "pushover analysis" [18]. The pushover curve is plotted in terms of top displacement and total base shear of the building, which represent the capacity of the structure. Then the pushover curve is transformed to capacity curve.

The elastic response spectrum curve is transformed to a demand curve in acceleration - displacement format (S_a vs S_d). The demand curve represents the earthquake. After that, overlap the demand curve and the capacity curve in terms of spectral displacement and spectral acceleration. The target displacement or structure performance point of an earthquake is the point where the demand and capacity curves graphically intersect. Fig. 2 illustrates a step-by-step pushover analysis in ATC 40 [19]

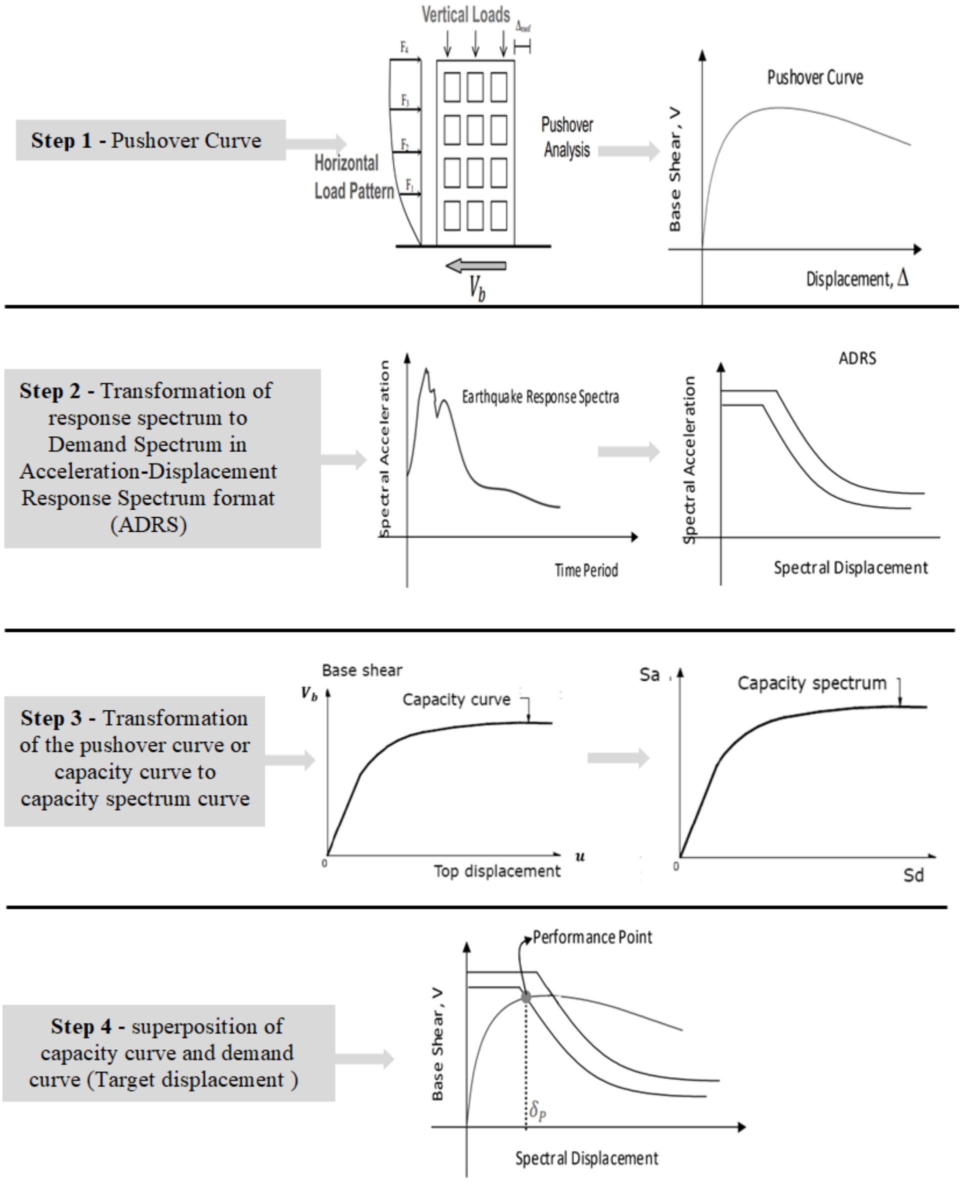

Fig.2 A step-by-step pushover analysis in ATC 40 [19]

3.2 TARGET DISPLACEMENT

The target displacement, or performance point determines building performance criteria and it can be evaluated using three methods as follows:

1) <u>The Capacity Spectrum Method (CSM)</u>

The Capacity Spectrum Method (CSM) is an effective method for seismic assessment and building design, presented by Freeman in 1978 [18]. ATC 40 provides information about the CSM [19].

2) **<u>The displacement coefficient method (DCM)</u>**

It is possible to estimate displacement demand by using the Displacement Coefficient Method (DCM), which is documented in FEMA 356 [20] and FEMA 273 [21].

3) <u>The N2 method</u>

Eurocode 8 [22] contains information about the N2 method, which is used for the estimation of the target displacement. In the N2 method, "N" means a non-linear seismic analysis and "2" means a two-dimensional structural model. Pushover analysis of multi degree of freedom (MDOF) and spectral analysis of equivalent single degree of freedom (ESDOF) are applied.

3.3 PERFORMANCE LEVEL OF STRUCTURES

Once the target displacement has been determined, the building's seismic performance can be assessed. Four lines (AB, BC, CD, and DE) formed the performance skeleton curve. these lines indicate the elastic stage, plastic stage, unloading stage, and failure stage, respectively.

According to the limits in FEMA 273 [21], as shown in **Fig. 3**, three levels of seismic performance were selected as the design basis: immediate occupancy (**IO**), which indicates that the structure is in the serviceability limit state; life safety (**LS**), which indicates that the structure is approaching the safety limit state; and collapse prevention (**CP**), which indicates that the structure is almost collapsing.

The global performance of the building is correlated with the inter-story drift ratio (IDR), which can be computed by dividing the target displacement by the height of the building. **Table 1** shows the inter-story drift ratio for each performance level in ATC-40 [19].

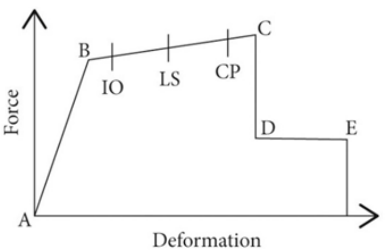

Fig.3 Performance level of structures in FEMA 273 [21]

- **Point A:** The origin.
- **Point B:** The yield point. No Plastic deformation occurs until a point B.
- **Point C:** The maximum capacity for the pushover analysis.
- **Point D:** The residual strength for the pushover analysis.
- **Point E:** the failure.

Table 1. Inter-story drift ratio for each level according to ATC- 40 [19]

Performance levels		
Immediate Occupancy	Damage Control	Life Safety
0.01	0.01 – 0.02	0.02

4. APPLICATION AND CASE STUDY

Trani's Cathedral Bell Tower is the proposed case study for the application of the pushover analysis method [1]. The numerical model for the tower was created using the finite element software ABAQUS [23] and the pushover analysis was applied to evaluate the seismic performance of the tower.

4.1 DESCRIPTION OF TRANI'S CATHEDRAL BELL TOWER

Trani's Cathedral is one of the most popular structures in Romagna, Italy, as shown in Fig. 4. The bell tower was constructed at the end of the eleventh century. The first level, which is about 14.30 meters high, is composed of an arch that connects the bell tower body and the cathedral. The second level, which is about 33.30 meters high, is composed of a square section with a dimension of 7.50 x 7.50 m. The third level, which is about 9.40 meters high, is composed of an octagonal section with a 2.30 m side and about 3.40 meters high. At the end of the octagonal section, there is a dome that is about 6.00 meters high. The total height of the bell tower is 57 m, and the wall thickness is about 1.40 m [1].

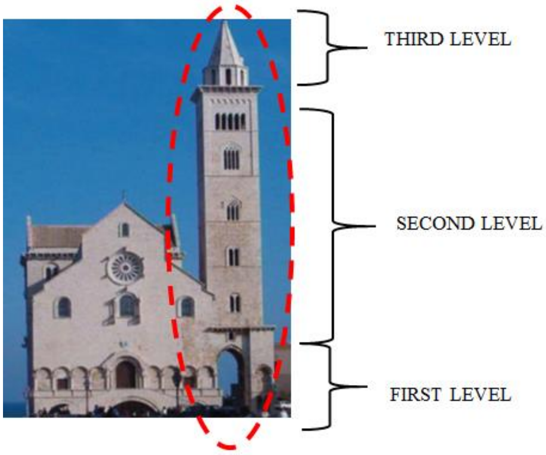

Fig.4 Trani's Cathedral Bell Tower, Italy [1] Italy [2]

4.2 NUMERICAL MODELING

4.2.1 APPROACHES FOR MASONRY MODELING

The nature of masonry construction can be represented using a variety of modeling techniques. The choice of modeling strategy depends on the required level of accuracy [24]. **Fig. 5** illustrates modeling for masonry buildings, which can be carried out using the following approaches:

a) Detailed Micro-Modeling

Masonry units were classified as discontinuous elements, while mortar joints and unit-mortar interfaces were classified as continuous elements as shown in **Fig. 5 (a)**.

b) Simplified Micro-Modeling

Masonry units were also defined as continuum elements, while mortar joints and unit-mortar interface as discontinuous elements as shown in **Fig. 5 (b)**.

c) Macro-Modeling

The combination of brick units and mortars was modeled as a continuous material by different nonlinear laws in tension and compression as shown in **Fig. 5 (c)** The comparison of the three modeling strategies leads to the conclusion that the macro-modeling strategy is more practice-oriented due to its lower memory and time needs. When a structure has large dimensions, the macro model is preferable.

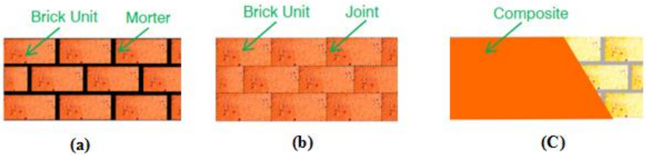

Fig.5 Finite element modeling approaches for masonry structures: (a) detailed micro modeling (b) Simplified micro-modeling (c) macro-modeling [24].

4.2.2 MATERIAL PROPERTIES

The mechanical properties of the masonry material of the tower used for the numerical model in terms of density and modulus of elasticity were obtained from previous studies [1]. Also, poisson's ratio was obtained from a previous study [25], as shown in **Table 2**. The Concrete damage plasticity (CDP) techniques are commonly used to determine the damage ratio in masonry structures, as proposed by Lubliner et al. [26]. The basic modeling parameters, which were taken from a study presented by Valente and Milani, are required to simulate the nonlinear behavior [27], as shown in **Table 3**. The stress-strain curves of the masonry used in the tower were taken from the study prepared by Kaushik et al. [28], as shown in **Fig. 6.**

Where dilation angle [Ψ] is Angle based on by a change in the material's volume after a shear force is applied, [f_{bo}/f_{co}] Ratio between the biaxial and uniaxial compression strength, and [K] refers to the ratio between the secondary stress constants in the tension and compression.

Table 2. Mechanical properties of masonry [1]

Elasticity Parameters	Values
Density, γ [kg/m3]	2460
Modulus of elasticity, **E** [MPa]	3200
Poisson's ratio , υ [25]	0.17

Table 3. Concrete damage plasticity Parameters of masonry [27]

Plasticity Parameters	Values
Dilatation angle, **[Ψ]**	10°
Eccentricity, **[e]**	0.10
Viscosity parameter	0.002
ratio [f_{bo}/f_{co}] Strength	1.16
Stress ratio **[*K*]**	0.67

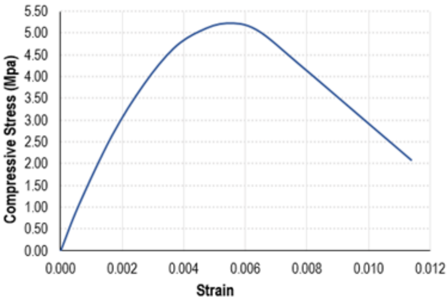

Fig.6 (a) Compression Stress-strain curves for masonry [28].

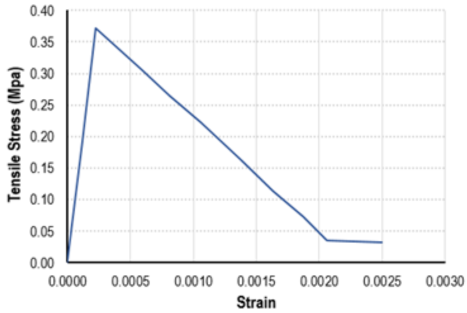

Fig.6 (b) Tensile Stress-strain curves for masonry [28].

4.2.3 FINITE ELEMENT MESH

In order to analyze Trani's Cathedral Bell Tower, Using the finite element program ABAQUS [23], a three-dimensional finite element model of the tower was created. The numerical model is divided into a mesh of solid finite elements for pushover analysis, as shown in **Fig. 7**. The analysis of the tower model was performed using a uniform mesh size of (800 x 800) mm. The interaction coupling is used as a reference point to evaluate the behavior of the tower. The reference point is located at the top of the tower for applying the lateral displacement, as shown in **Fig. 8**.

4.3 MODEL VERIFICATION AND NUMERICAL RESULTS

The pushover curve obtained from the proposed finite element model in the current study was compared to the pushover curve from Diaferio et al. [1] to verify the validity of numerical simulations. **Fig.9** compares the pushover curve from the proposed finite element model up to lateral displacement equal to 100 mm with the published pushover curve. The plotted pushover curve from the current study was found to agree with the published ones. The finite element model can be used to evaluate the seismic performance of the investigated tower.

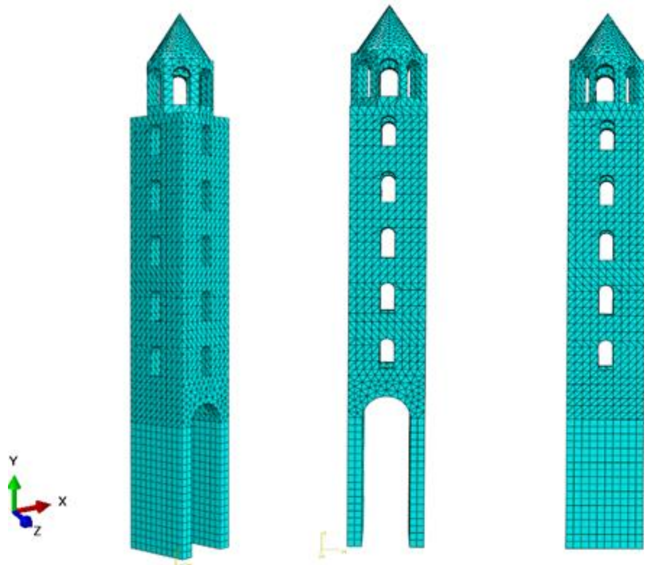

Fig.7 Finite element meshes for Trani's Cathedral Bell Tower

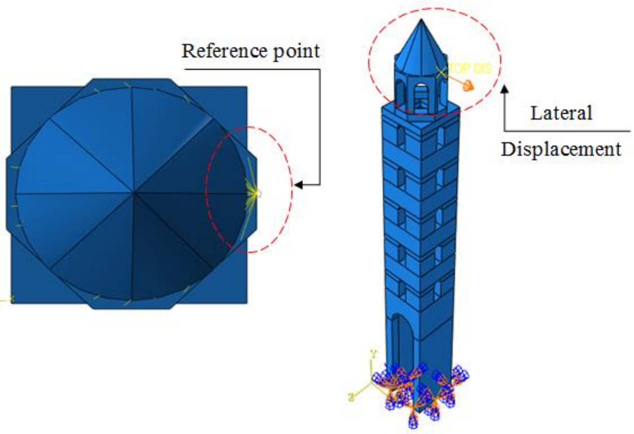

Fig.8 Reference point of Applying Lateral Displacement

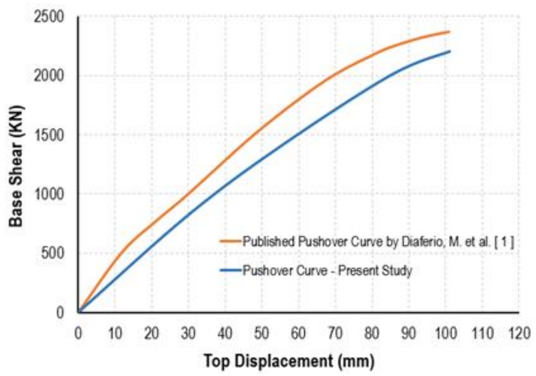

Fig.9 pushover curve and the published pushover curve [1]

According to the results of the pushover analysis from the numerical model of the tower, it can be concluded that:

- The maximum displacement value resulting from the pushover was 800 mm in the x-direction, as shown in **Fig.10**.
- The maximum tension stress for the stresses (S11) at the X-direction resulting from the pushover analysis was 0.27 MPa, and the maximum compression stress was 4.21 MPa. Similarly, for the stresses (S22) at the Y-direction, the maximum tension stress was 0.36 MPa, and the maximum compression stress was 10.51 MPa, as shown in **Fig.11**.
- The patterns of crack growth of Trani's Cathedral Bell Tower during pushover analysis is shown in **Fig.12**. Crack pattern proved that the cracks started from the eight top columns. The start and growth of cracks indicated that most of the tensile stresses happen in these parts. The top eight columns supporting the top dome were found to be the weakest areas of the tower body and the bottom curved arch. Diagonal cracks also appeared around the opening of the tower. • The Pushover Curve in **Fig. 13** shows nonlinear behavior of the tower, this behavior is caused by excessive loads applied to the tower model, which results in a decrease in the strength and stiffness of the structural elements and changes in their properties from elastic to plastic. Based on this curve, it can be determined that the tower can withstand ultimate base shear of 3200 kN and ultimate displacement of 220 mm.

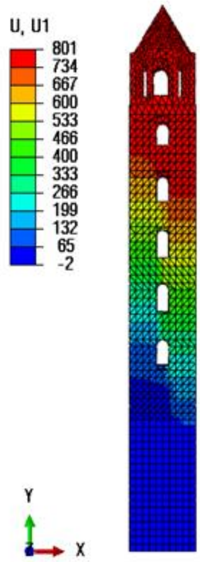

Fig.10 Displacement in X-dir (mm)

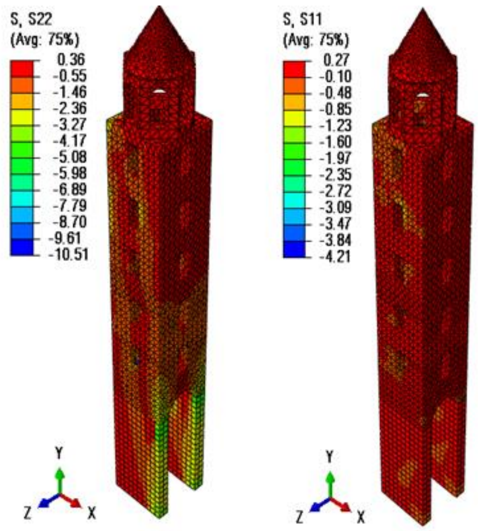

Fig.11 Stresses (S11) and (S22) from Pushover in X-direction (Mpa)

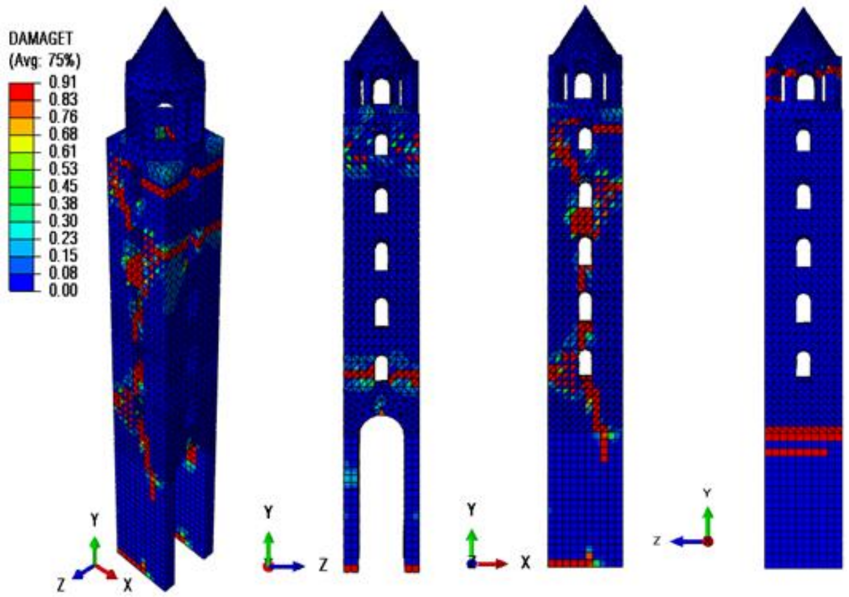

Fig.12 Cracks Pattern of Trani's Cathedral Bell Tower

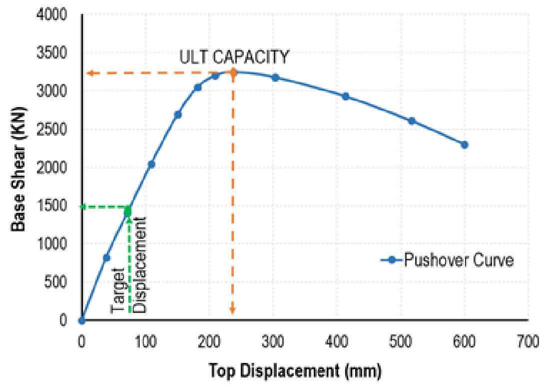

Fig.13 Pushover Curve in terms of top displacement and Base shear

4.4 TARGET DISPLACEMENT OR PERFORMANCE POINT

The seismic assessment was carried out using the **N2** method (EC8, 2004) [22] according to the following steps:

A- **Determine elastic spectrum in Acceleration - Displacement format** as shown in **Fig.14**.

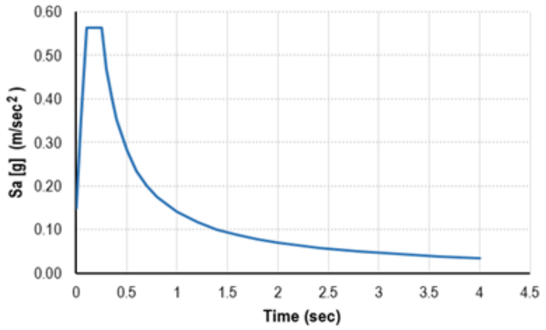

Fig.14. Elastic Response Spectrum

Using the following equation to convert elastic response spectrum to response spectrum in Acceleration - Displacement format, which called demand curve [21], as shown in **Fig.15**

$$S_{de} = \frac{T^2}{4\pi^2} * S_{ae} \quad (1)$$

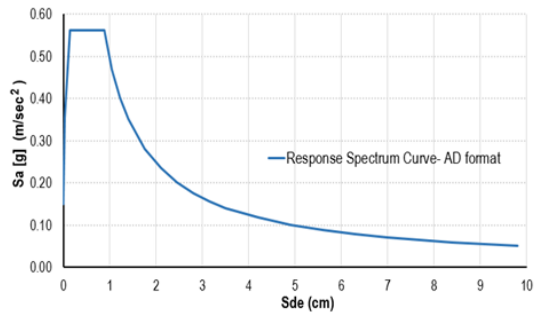

Fig.15. Elastic Response Spectrum in acceleration - displacement format

B- **Convert the Pushover curve to a Bilinear curve, as shown in Fig.16**

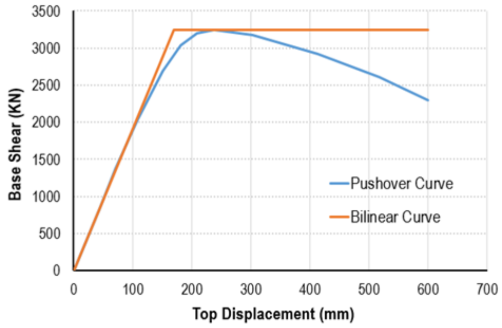

Fig.16 Pushover curve and Bilinear curve

C- Convert a bilinear curve to a capacity curve.

Using the following equation to convert bilinear curve to capacity curve in Acceleration -Displacement format [21], as shown in Fig.17.

$$S_a = \frac{Base\ shear}{mass}\ m/sec^2 \quad (2)$$

Sa (g) = Sa / 9.81 m/s2 (3)

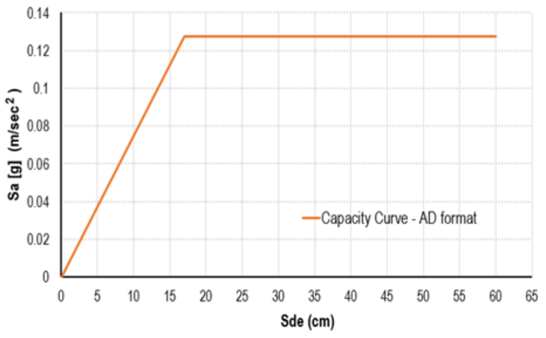

Fig.17. Capacity curve of the tower

D- Performance point (target displacement)

- The value of performance points can be concluded as shown in **Fig. 18**. The orange line is the capacity curve, while the blue line is the elastic response spectrum curve. The target displacement of the tower is equal to 80 mm and is the point where the capacity spectrum curve and the elastic response spectrum curve intersect.
- The tower can withstand seismic base shear up to 1500 kN, or approximately 47% of its ultimate capacity (3200 kN), as calculated from the pushover curve. Also, the target displacement of 80 mm is equivalent to approximately 36% of the ultimate displacement (220 mm), as indicated by the pushover curve in **Fig. 13** and the performance point (target displacement) in **Fig. 18**.

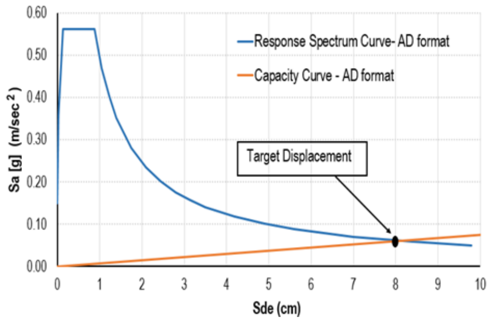

Fig.18 Performance Point (target displacement) of the tower

4.5 PERFORMANCE LEVEL OF THE TOWER

Based on Table 1, the determination of the performance level of the structure follows the ATC-40 [19]. The results showed that the structural performance was at the level of 0.0014 (drift ratio), the ratio can conclude that the building is in the Immediate Occupancy (IO) category, as shown in Table 4.

Table 4. Terani tower performance level according to ATC-40 [19]

Parameter	Results
Target Displacement Δ (mm)	80
Drift ratio (Δ / H_{total})	(0.08/57) = 0.0014 < 0.01
Performance level	Immediate Occupancy (IO)

In order to verify the validity of the computed target displacement in the current study, a comparison between the target displacement is presented in Table 5. Diaferio et al. [1] used three risk assessment criteria to evaluate the displacement capacity of the tower: Rankine criterion, maximum tensile stress and Coulomb criterion. The computed target displacement using N2 method was found to agree with the published ones.

Table 5. comparison between the target displacements

Target Displacement Method	Rankine criterion	Maximum tensile stress	Coulomb criterion	N2 method [22]
Target Displacement (mm)	100	65	85	80
	Diaferio et al. [1].			Current Study

CONCLUSIONS

A numerical study had been carried out to assess the seismic performance of the Terani Cathedral bell tower using pushover analysis. The performance level of the tower had been evaluated according to the ATC-40. Based on the pushover analysis results of the Terani Cathedral bell tower, the following conclusion can be drawn:

1. The basic concept of pushover analysis was explained to provide an efficient tool and procedure to assess the seismic performance of heritage masonry structures.
2. The developed numerical model simulates the accurate behavior of Terani Cathedral bell tower and predicts the crack pattern, stresses, and pushover curve. As a result, appropriate action can be taken for rehabilitation purposes.
3. The maximum displacement value resulting from the pushover was 800 mm in the x-direction.
4. Under pushover analysis, it is observed that the maximum stresses were concentrated around the opening, the maximum tension stress (S11) at X-

direction was 0.27 MPa and the maximum compression stress was 4.21 MPa, and for the stresses (S22) at Y-direction, the maximum tension stress was 0.36 MPa and the maximum compression stress was 10.51 MPa .

5. The octagonal section supporting the top dome were found to be the weakest areas of the tower body, and diagonal cracks also appeared around the opening and bottom curved arch.
6. The tower can withstand seismic base shear up to 1500 kN, or approximately 47% of its ultimate capacity (3200 kN). Also, the target displacement of 80 mm is equivalent to approximately 36% of the ultimate displacement (220 mm).
7. The target displacement is 80 mm, and the tower's performance level indicates that it is in the immediate occupancy (IO) category. This means that when an earthquake occurs, the structure does not experience structural or non-structural damage, and the loss of life is low so that it can be immediately reused. Overall, these findings showed that the building is safe.

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